https://ntrs.nasa.gov/search.jsp?R=19950002748 2020-06-17T23:43:36+00:00Z

N95- 70868

CFD ASSESSMENT OF THE CARBON MONOXIDE AND NITRIC OXIDE FORMATION FROM RD-170 HOT-FIRE TESTING AT MSFC

Ten-See Wang and Paul McConnaughey

NASA Marshall Space Flight Center, Huntsville, Alabama 35812

Saif Warsi

Sverdrup Technology, Inc., Huntsville, Alabama 35806

and

Yen-Sen Chen

Engineering Sciences, Inc., Huntsville, Alabama 35805

SUMMARY:

Computational Fluid Dynamics (CFD) technology has been used to assess the exhaust plume pollutant environment of the RD-170 engine hot-firing on the F1 Test Stand at Marshall Space Flight Center. Researchers know that rocket engine hot-firing has the potential for forming thermal nitric oxides (NO_x), as well as producing carbon monoxide (CO) when hydrocarbon fuels are used. Because of the complicated physics involved, however, little attempt has been made to predict the pollutant emissions from ground-based engine testing, except for simplified methods which can grossly underpredict and/or overpredict the pollutant formations in a test environment. The objective of this work, therefore, has been to develop a technology using CFD to describe the underlying pollutant emission physics from ground-based rocket engine testing. This resultant technology is based on a three-dimensional, viscous flow, pressure-based CFD formulation, where wet CO and thermal NO_x finite-rate chemistry mechanisms are solved with a Penalty Function method. A nominal hot-firing of a RD-170 engine on the F1 stand has been computed. Pertinent test stand flow physics such as the multiple-nozzle clustered engine plume interaction, air aspiration from base and aspirator, plume mixing with entrained air that resulted in contaminant dilution and afterburning, counter-afterburning due to flame bucket water-quenching, plume impingement on the flame bucket, and restricted multiple-plume expansion and turning have been captured. The predicted total emission rates compared reasonably well with those of the existing hydrocarbon engine hot-firing test data.

DISCUSSION:

RD-170 is a regeneratively cooled, four-nozzle clustered engine which burns Kerosene fuel with liquid oxygen and was used to thrust Energia launch vehicles. Thermochemical analysis was performed for the thrust chamber at a nominal operating condition and the equilibrium products at the nozzle exit were used as the input to the propulsion system. $CH_{1.9423}$ was used as the chemical formula for Kerosene fuel. The analysis indicated that a significant amount of CO (24.569%) existed at the nozzle exit. This is the amount that could be dumped into the environment and can only be chemically reduced through afterburning. To accurately predict the contaminant concentrations of the exhaust plume, finite-rate chemical kinetics are included in the numerical modeling. The plume chemistry occurring in the flame-bucket/test-stand flow physics includes the afterburning of CO to CO_2, thermal NO_x formation and decomposition, counter-afterburning effect on CO conversion due to water quenching and its reduction effect on NO_x formation. These are described with a wet CO and a thermal NO_x finite-rate mechanisms. Production of thermal NO_x is generally negligible at low temperatures. It is therefore expected that most of the thermal NO_x will be formed in the flame front, .i.e., the plume mixing layer near the exit plane of the nozzles.

The F1 Test Stand, standing 230 feet tall with a flame bucket (deflector) attached to the aspirator, was used to test F1 engines with which Saturn launch vehicles were propelled. Not only does the flame bucket quenches the rocket exhaust plume with deluge water, but also turns the vertical flowing exhaust plume to that of a horizontal direction, after which the plume expands and dissipates into the atmosphere. Fig. 1 shows the computational domain for the F-1 Stand. The RD-170 engine is mounted vertically, firing down into the flame bucket. Due to symmetry, only half of the domain was actually computed. The four RD-170 nozzles (mounted beneath the platform that is not modeled) and the aspirator are described by Zone 1 which contains 63,360 grid points. The aspirator itself is mounted on top of the flame bucket such that the air entrainment can be promoted and the plumes are centered while impinging at a predetermined area in the flame bucket (approximately 45-degree elbow at the bottom). Ambient air is allowed

to be entrained through the top and four side boundaries of Zone 1. The flame bucket is modeled by Zone 2 which composes of 72,000 grid points. The plumes are then quenched through water deluge injecting from all four walls inside the bucket. The water injection pattern is designed as such that most of the water injects at the plume impingement area. After passing through the flame bucket, the quenched plumes expand into the vast surrounding atmosphere (Zone 3, not shown) which is described by 156,975 grid points.

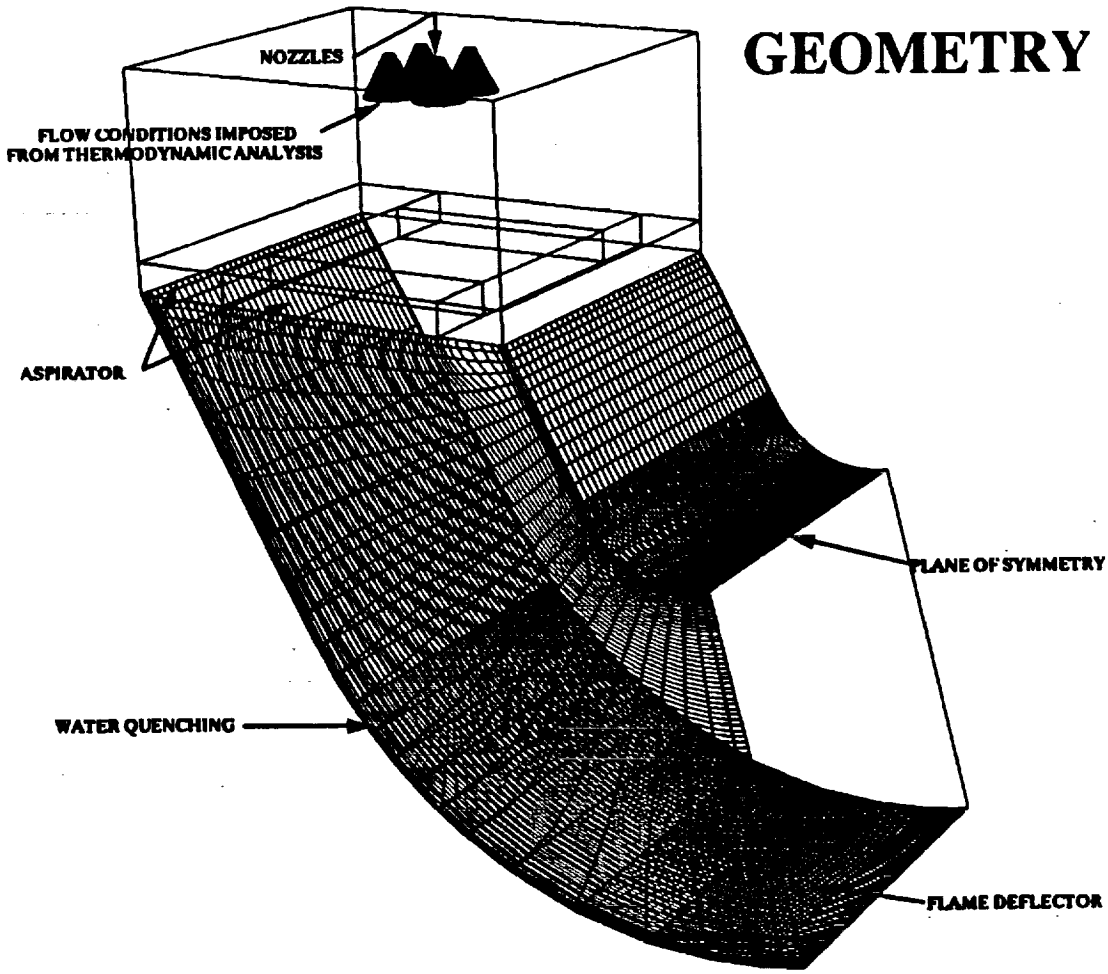

Fig. 1 Computational domain for the RD-170 nozzles and F1 Test Stand.

A frozen chemistry analysis was performed at first for a small period of elapsed time in order to establish an initial plume in the system. This not only prepared for the initial flowfields for the computation of subsequent parallel finite-rate chemistry and finite-rate chemistry with water-quenching cases, but also served as an excellent check of mass conservation using carbon balance. This procedure is allowed since the total pollutant emission rates during a nominal steady RD-170 hot-firing are desired and not those of an actual start-up sequence. The goals are therefore to compute the growth rate of NO_x and the disappearance rate of CO until they achieve asymptotic states. The result of the computation indicated a large amount of air was entrained through the aspirator. Entrained from surroundings close to the open platform, the air accelerated and mixed with the plume boundary layer and entered the opening of the aspirator, where it continuously mixed with the advancing plume boundary layer. In addition to cooling and dilution of the contaminant, the entrained air also provides the source of reactants for afterburning and thermal NO_x formation. Most of the thermal NO_x is formed near the aspirator level where it has the most mixing and the hottest temperature. This is in agreement with the characteristics of the Zeldovich mechanism. It can also be seen that the plumes impinge on the 45-degree bend section of the flame bucket where it encounters the most water-quenching, that agrees with the original design. The quenched plumes then turn and partially hit the outer wall, where it moves horizontally out, following the direction of the flame bucket.

The averaged mass fraction for CO in the add water-quenching case is more than that of the purely finite-rate chemistry case due to the counter after-burning effect of deluge water, and vice versa for that of CO_2. The higher level of OH in the finite-rate case shows a higher degree of after-burning reaction, due to higher overall plume temperature without water-quenching. Total NO_x production drops significantly in the add water-quenching case. The concentration of NO_x in the add water-quenching case is almost two orders of magnitude lower than that in the finite-rate chemistry only case. This is not surprising since the extent of thermal NO_x formation depends heavily on the local temperature. The effect of water deluge on the formation of NO_x is the reduction in peak temperature caused by the heat capacity of water. The computations were stopped when the growth rates of the plumes reached their approximate asymptotic states. Obviously, the plume energy of the finite-rate chemistry is higher than that of the add water-

quenching case. Correspondingly, the plume volume growth rate of the finite-rate case is larger than that of the add water-quenching case. These CFD results ultimately serve as the basis (input) for the subsequent meteorological cloud dispersion calculation, where the plume volume growth rate helps determining the eventual plume size and the plume energy growth rate helps determining the magnitude the plume buoyancy force.

A comparison of the calculated criteria pollutant total emission rates for RD-170 with those measured for other Kerosene-fueled engines is shown in Table 1. Since thrust levels are quite different, the measured emission rates were extrapolated to a RD-170 level by thrust ratios. Although the operations of the engines and test stands are vastly different, and there is a question on whether the point sampling technique used in the measurement representative of the whole plume. The agreement in terms of order-of-magnitude for these engines is reasonable and encouraging. Among RD-170 CFD computations, the emission rate of CO is maximum and that of NO_x is zero for the frozen chemistry case, since afterburning reactions are not turned on, whereas the effect of water deluge has reduced the CO conversion rate from 83% of the finite-rate chemistry case to that of 67%. This is of interest since the effect of water deluge also has reduced the NO_x production by 95%.

Table 1. Total emission rates

Engine	Thrust, lbf	NO_x, lb/sec	CO, lb/sec
MA5B/hot-firing	370,000	5.4/25.9*	133/641*
MA3S/hot-firing	165,000	2.7/29.1*	210/2,266*
MA3B/hot-firing	60,000	1.5/45.6*	138/4,111*
RS27/hot-firing	205,000	1.2/10.6*	94/820*
RD-170/CFD			
Frozen	1,777,000	-	1,382
Finite-Rate	1,777,000	8.0	232
Add Water	1,777,000	0.4	463

* based on extrapolation of measured emission rate to a RD-170 by thrust ratio